

APPLICATION

OF

Shibin Jiang
Christine P. Spiegelberg
Tao Luo

FOR

UNITED STATES LETTERS PATENT

ON

SINGLE-FREQUENCY NARROW LINEWIDTH $2\mu\text{M}$ FIBER LASER

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ASSIGNED TO

NP Photonics, Inc.

SINGLE-FREQUENCY NARROW LINEWIDTH 2 μ M FIBER LASER

CROSS-REFERENCE TO RELATED APPLICATIONS

5 This application claims benefit of priority under 35 U.S.C. 120 to U.S. application Serial No. 10/056,830 entitled "Rare-Earth Doped Phosphate-Glass Single-Mode Fiber Lasers" filed on January 24, 2002, the entire contents of which are incorporated by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

10 This invention relates to fiber lasers and more specifically to a single frequency 2 μ m fiber laser with narrow linewidth (<100 kHz and preferably <10 kHz) formed from glass fibers doped with Thulium and Holmium oxides and mixtures thereof.

Description of the Related Art

20 Rare-earth doped glass fiber lasers were first proposed in the 1960s and have received considerable attention in the 1980s for potential applications in optical communication. For laser emission to occur, the active fiber is placed inside a resonant cavity. The optical feedback can be provided simply by the reflectivity of the end facets, by mirrors, by distributed feedback Bragg (DFB) gratings, or by distributed Bragg reflectors (DBR), or by constructing a ring cavity structure. Laser emission occurs when the total gain overcomes the losses in the cavity. Hence, a minimum gain has to be achieved to reach the laser threshold condition. Typical fiber lasers lase in a great number of

longitudinal modes in single transverse mode optic fibers, the so-called "single mode fibers". A "single frequency" fiber laser lases at a single longitudinal mode.

Most telecommunications applications operate at a wavelength of 1.55 μ m to take advantage of the absorption characteristics of silica fiber. 1.55 μ m single-frequency lasers using Er³⁺ doped silica or silica-based fibers are described in G.A. Ball, W.W. Morey, W.H. Glenn, IEEE Photonics Technology Letters, Vol. 3, No. 7, July 1991; W.H. Loh et al. *Journal of Lightwave Technology*, Vol. 16, No.1, pp. 114-118 January 1998; and US Patents 5,305,335 and 5,237,576.

2 μ m lasers are important because of the high transmission properties in air at that wavelength. Applications such as seeder lasers, LIDAR, optical heterodyne systems, nonlinear frequency conversion, coherent satellite communication, and distributed sensing require a robust 2 μ m, e.g. typically 1.8-2.1 μ m, single frequency narrow linewidth fiber laser. Single-frequency operation with a linewidth less than 100 kHz, preferably less than 10 kHz, provides both the resolution and long coherence needed by these applications. The 2 μ m laser would preferably have sufficient output power without the need for a booster amplifier in order to maintain the high signal to noise ratio.

Current 2 μ m single frequency laser technology is limited to solid state lasers, which are either configured to use an intracavity diode pumped etalon in conjunction with an external reference etalon (US Patent 5,457,706 to McGuckin) or as a non-planar ring oscillator (NPRO) in the presence of a sufficiently strong magnetic field (US Patents

4,578,793 and 5,043,996).

Current 2 μ m fiber laser technology is limited to single transverse mode performance. J. Y. Allain et al *Electronics Letters* 25, 1660 (1989) reported on a single transverse mode laser operation at 1.88 and 2.35 μ m using a 150 cm long thulium doped fluorozirconate fiber. J. N. Carter et al *Electronics Letters* 26, 599 (1990) reported on a cw thulium doped fiber laser that emits at 1.97 μ m using the $^3H_4 - ^3H_6$ transition in a multimode fluoride glass fiber. Cladding pumped Tm doped silica fiber laser at 2 μ m were reported by R.A. Hayward et al *Electronics Letters*, Vol. 36, No. 8, pp.711 (2000), S. Jackson et al, *Journal of Optical Society of America B*, Vol. 16, No. 12, pp.2178 (1999), *Optics Letters*, Vol. 23, No. 18, pp.1462 (1998), and W.A. Clarkson et al, *Optics Letters* Vol. 27, No. 22, pp.1989, (1989). Mode-locked thulium fiber laser was described by R.C. Sharp et al *Optics Letters*, Vol.21, No. 12, pp.881, (1996). Q-switched high peak power operation at 2 μ m in Tm doped silica fiber was reported by A.F. El-Sherif et al *Optics Letter*, Vol. 28, No.1, pp.22, (2003). Fiber laser operation in thulium sensitized holmium doped silica fibers were reported by K. Oh, et al *Optics Letters*, Vol.19, No. 4, pp. 278 (1994), C. Ghisler et al *IEEE Journal of Quantum Electronics*, Vol. 31, No. 11, pp.1877, (1995), and S. D. Jackson et al *IEEE J. of Quantum Electronics*, Vol. 34, No. 9, pp.1578 (1998).

SUMMARY OF THE INVENTION

The present invention provides a compact single frequency, single-mode 2 μ m fiber laser with narrow linewidth.

The 2 μ m fiber laser includes a gain fiber formed of a low phonon energy glass host, either fluoride based or an oxide-based multi-component glass such as germanate or tellurite, that is doped with triply ionized rare-earth
5 thulium or holmium oxide or mixtures thereof. Erbium and ytterbium may be used to absorb and transfer pump energy to the active ions. Fiber gratings are formed in sections of passive silica fiber and fused to the gain fiber to form the resonant cavity. A doping concentration of 0.5 to 15 wt. %
10 for either thulium or holmium oxides or mixtures thereof produces adequate gain, hence output power levels for fiber lengths less than 5cm and preferably less than 3cm to enable stable single-frequency operation. Formation of the gratings in passive silica fiber both facilitates splicing to other
15 optical components and reduces noise thus improving linewidth. The pump can be a multimode or single mode laser. In the case of a single mode laser, the use of a polarization maintaining (PM) fiber in the pump source further improves wavelength stability, linewidth and
20 vibration/acoustic sensitivity.

In another embodiment, the gain fiber is a polarization maintaining (PM) fiber, which reduces the noise level in the laser and improves output power stability. As a result of their specific local environment, the active
25 ions experience an anisotropy that leads to polarization dependent gain, which means that the gain spectra for two different polarization components are not the same. Combining polarization selective feedback with a polarization maintaining active fiber reduces the low
30 frequency noise that results from random polarization fluctuations inside the laser cavity.

These and other features and advantages of the invention will be apparent to those skilled in the art from the following detailed description of preferred embodiments, taken together with the accompanying drawings, in which:

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BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram of a single-frequency fiber laser in accordance with the present invention;

FIGs. 2a and 2b are a plot of the absorption spectra of thulium and holmium doped glasses, respectively;

FIG. 3 is a diagram of the longitudinal mode spacing and grating bandwidth that produce a single-frequency output;

FIG. 4 is a sectional view of the gain fiber;

FIGs. 5a and 5b are diagrams of a packaged single-frequency fiber laser including temperature control and vibration isolation; and

FIG. 6 is a diagram of a pump source with a PM fiber.

DETAILED DESCRIPTION OF THE INVENTION

The present invention provides a compact single frequency, single-mode $2\mu\text{m}$ fiber laser with narrow linewidth, less than 100 kHz and preferably less than 10 kHz. As shown in figures 1 through 4, a $2\mu\text{m}$ fiber laser includes a single mode gain fiber 12 formed of a low phonon energy glass host doped with triply ionized rare-earth thulmium or holmium oxide or mixtures thereof. Erbium or ytterbium dopants may also be used to absorb and then transfer pump energy to the active ions. The low phonon energy glass host is selected from either an oxide-based multi-component germanate or tellurite glasses or a fluoride

based glass. These host glasses have sufficiently low phonon energy to slow down the multi-phonon relaxation process. Narrowband and broadband fiber gratings 14 and 16, respectively, are formed in sections of passive silica fiber 18 and 20 and fused to the ends of gain fiber 12 to form a resonant cavity that provides the feedback necessary to sustain laser operation. The reflectivity of the broadband grating 16 should be as close to 100% as possible. The reflectivity of the narrowband grating 14 is less than 100%, suitably 30-90% depending upon the pump power and target output power, such that power can be removed from the cavity. Alternately, the broadband grating could be used to output couple the laser energy.

The low phonon energy glasses (germanate, tellurite and fluoride) exhibit high quantum efficiency for the $2\mu\text{m}$ transition. These glasses also support the high doping concentrations required to provide sufficient gain in short fiber lengths to achieve both single frequency operation and narrow linewidths. The holmium oxide (Ho_2O_3) or thulium oxide (Tm_2O_3) doping concentration is 0.5-15 wt. %. If co-doped, the thulium/holmium concentration can range from 0.5 to 15 wt. %. The formation of the gratings in passive silica fiber rather than the gain fiber reduces ASE noise, which improves linewidth. As will be described with reference to figures 5a and 5b, thermal stabilization and vibration isolation of the gain fiber and gratings and the use of a polarization maintaining (PM) fiber in the pump source further improve and maintain linewidth in commercial applications.

A source of pump radiation 22, e.g. a single-mode or multi-mode laser diode, illuminates gain fiber 12 at a

wavelength, typically 800nm, within the absorption band. As shown in figure 2a, the absorption band **24a** of triply ionized thulium occurs from 750 to 820 nm. The pump wavelength can be around 1.2 μ m and 1.7 μ m to excite Thulium from 3H_6 state to 3H_5 and 3F_4 levels. As shown in figure 2b, the absorption band **24b** of triply ionized holmium occurs from 1800 to 2100 nm. The pump wavelength can be around 1800 μ m and 2100 μ m to excite Holmium from 5I_8 to 5I_7 levels. Typically one excites thulium ions, which in turn transfers energy to the holmium ions. The pump wavelength can also be shifted to other wavelengths to excite Yb and Er when these ions are doped into the host. Pumping of the doped glass populates the thulium upper level creating a population inversion. Spontaneous emission catalyzes the stimulated emission of the thulium (holmium) ions in the upper level over a range of 1800 to 2000nm (1900 to 2200nm). The emission peak of thulium (holmium) occurs at a wavelength of approximately 1800nm (2080nm).

Laser emission occurs when the total gain produced by stimulated emission overcomes the losses in the cavity. The gain profile of thulium and holmium and the geometry of the resonant cavity create preferential feedback so that laser emission only occurs at one or more discrete wavelengths. As shown in figure 3, an ultra-short cavity, less than 5cm and preferably less than 3cm, produces a mode spacing $\Delta\nu$ that is at least comparable to and preferably larger than the linewidth **30** (full-width half-max of the peak) of the narrowband grating (less than 0.07 nm), which together with the gain spectrum **31** limits laser emission to a single longitudinal mode **32**. Therefore, a very high gain per unit length is needed in order to achieve single frequency fiber

laser operation if a linear cavity is used. The gain per unit length required here typically exceeds normally achievable value. Glasses with high doping concentration and fibers with high gain per unit length are required. In addition, a fusion splicing technique with a short working distance between the active fiber and the grating fibers is needed.

To achieve single-frequency performance the glass host must support high Thulium and Holmium doping concentrations to realize the necessary gain per unit length. The doping concentrations are at least 0.5 wt. % and typically about 1-8 wt. %. Therefore, glasses with good rare-earth ion solubility must be selected.

Suitable oxide-based multi-component laser glasses contain either a germanate-oxide (GeO_2) or tellurite-oxide (TeO_2) network former, one or more glass network modifiers including alkaline-earth oxides and transition metal oxides MO such as BaO , CaO , MgO , SrO , ZnO , PbO and mixtures thereof and/or alkali metal oxides R_2O such as Na_2O , Li_2O and K_2O and mixtures thereof, and one or more glass network intermediators L_2O_3 such as Y_2O_3 , La_2O_3 , Al_2O_3 , B_2O_3 , WO_3 and mixtures thereof. The modifier modifies the glass network, thereby reducing its melting temperature and creating additional dopant sites. The intermediary bridges some of the bonds in the network thereby increasing the network's strength and chemical durability without raising the melting temperature appreciably. The glass host composition by weight percent is 30 to 85 % network former, 2 to 50 % modifier including 0-10 % MO and 0-20 % R_2O , and 0.2 to 50 % intermediary. Typically, the intermediary is at least 2 wt. % and suitably 10 wt. % and the total modifier is at

least 2 wt. % and suitably 25 wt. %.

As shown in figure 4, the fiber core 40 is made up of the glass host doped with high concentrations of thulium or holmium oxide or mixtures thereof. The cladding layer(s) 42 are formed from the same glass host, although the exact composition may vary somewhat from the core glass, and are typically undoped. Numerous glass compositions were characterized for thermal properties (crystallization, expansion coefficient, transition and softening temperatures, core-to-clad similarity), chemical durability, ability to host high Tm (Ho) doping concentrations without quenching, spectroscopic properties (maximum emission cross-section at 2.0 microns), linewidth (maximum breadth at 2.0 microns) and refractive index to determine a range of wt.% for each ingredient that are acceptable. Suitable glass compositions for germinate host glasses are illustrated in Tables 1 and 2 and tellurite host glasses are illustrated in Table 3, respectively.

CG-S-3

	GeO	Al ₂ O ₃	BaO	Na ₂ O	Ho ₂ O ₃	Total
Wt%	61.82	7.36	17.29	6.71	6.82	100

DG-S-1

	GeO	Al ₂ O ₃	BaO	Na ₂ O	La ₂ O ₃	Total
Wt%	62.41	7.43	17.46	6.77	5.93	100

DG-S-4

	GeO	Al ₂ O ₃	BaO	Na ₂ O	La ₂ O ₃	Total
Wt%	62.41	7.43	17.46	6.77	5.93	100

DG-S-6

	GeO	Al ₂ O ₃	BaO	Na ₂ O	La ₂ O ₃	Total
Wt%	62.41	7.43	17.46	6.77	5.93	100

Table 1

	GeO ₂	Al ₂ O ₃	BaO	CaO	MgO	Na ₂ O	Li ₂ O	K ₂ O	La ₂ O ₃	Total
CG-S-1	65.50	8.00	12.50			12.00			2.00	100.00
G-S-1	65.50	8.00	24.50			0.00			2.00	100.00
G-S-2	65.50	8.00	18.00			6.50			2.00	100.00
G-S-3	65.50	8.00	12.50			12.00			2.00	100.00
G-S-4	65.50	8.00	6.50			18.00			2.00	100.00
G-S-5	65.50	8.00	0.00			24.50			2.00	100.00
G-S-6	65.50	8.00	6.50			18.00			2.00	100.00
G-S-7	65.50	6.00	6.50			20.00			2.00	100.00
G-S-8	65.50	4.00	6.50			22.00			2.00	100.00
G-S-9	65.50	2.00	6.50			24.00			2.00	100.00
G-S-10	61.50	6.00	6.50			24.00			2.00	100.00
G-S-11	57.50	6.00	6.50			28.00			2.00	100.00
G-S-12	65.50	6.00		6.50		20.00			2.00	100.00
G-S-13	65.50	6.00			6.50	20.00			2.00	100.00
G-S-14	61.50	6.00	6.50	4.00		20.00			2.00	100.00
G-S-15	61.50	6.00	6.50				24.00		2.00	100.00
G-S-16	61.50	6.00	6.50					24.0	2.00	100.00
G-S-17	57.5	6	10.5			24			2	100.00
G-S-18	53.5	6	14.5			24			2	100.00
G-S-19	60	6	8			24			2	100.00
G-S-20	60	6	6.5			25.5			2	100.00
G-S-21	60	6	6.5			20		5.5	2	100.00
G-S-22	60	6	4.5	2		20		5.5	2	100.00
G-S-23	60	7.5	6.5			24			2	100.00

Table 2

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	Na ₂ O	Al ₂ O ₃	B ₂ O ₃	TeO ₂	Tm ₂ O ₃	Total wt%
TB - T1	7.4	8.11	8.31	76.18		100
TB -T2	7.38	8.09	8.29	75.99	0.25	100
TB -T3	7.36	8.07	8.27	75.8	0.5	100
TB-T4	7.25	7.95	8.15	74.69	1.96	100
TB -T5	7.18	7.87	8.07	73.96	2.92	100

TB-T6	7.05	7.72	7.91	72.55	4.77	100
TB-T7	6.92	7.58	7.76	71.2	6.54	100
	K₂O	Li₂O	WO₃	TeO₂	Tm₂O₃	Total wt%
TW-T1	4.33	1.38	35.46	58.58	0.25	100
TW-T2	2.33	2.58	35.67	58.92	0.5	100
TW-T3	2.31	2.57	35.49	58.63	1	100
TW-T4	2.29	2.54	35.14	58.05	1.98	100

Table 3

Based on this empirical data, a first exemplary
5 embodiment of a suitable core laser glass may comprise by weight percent:

45 to 70 GeO₂;

0.5 to 20 L₂O₃ selected from Al₂O₃, B₂O₃ and La₂O₃ and mixtures thereof;

10 2 to 20 MO selected from BaO, CaO and MgO and mixtures thereof;

2 to 30 R₂O selected from Na₂O, Li₂O, and K₂O and mixtures thereof; and

0.5-15 Ho₂O₃, Tm₂O₃ and mixtures thereof.

15 Based on this empirical data, a second exemplary embodiment of a suitable core laser glass may comprise by weight percent:

45 to 85 TeO₂;

0.5 to 15 L₂O₃ selected from Al₂O₃, B₂O₃ and La₂O₃ and
20 mixtures thereof;

0.5 to 20 R₂O is selected from Na₂O, Li₂O, and K₂O and

mixtures thereof; and

0.5-15 Ho_2O_3 , Tm_2O_3 and mixtures thereof.

Based on this empirical data, a third exemplary embodiment of a suitable core laser glass may comprise by
5 weight percent:

45 to 85 TeO_2 ;

10 to 45 WO_3 ; and

0.5 to 20 R_2O selected from Na_2O , Li_2O , and K_2O and mixtures thereof; and

10 0.5-15 Ho_2O_3 , Tm_2O_3 and mixtures thereof.

In another embodiment, the gain fiber 12 is a polarization maintaining (PM) fiber, which reduces the noise level in the laser and improves output power stability. As a result of their specific local environment, the active
15 ions experience an anisotropy that leads to polarization dependent gain, which means that the gain spectra for two different polarization components are not the same. Combining polarization selective feedback with a polarization maintaining active fiber reduces the low
20 frequency noise that results from random polarization fluctuations inside the laser cavity.

The subclass of multi-component glasses has a much lower softening temperature ($<600^\circ\text{C}$) than silica ($>1200^\circ\text{C}$), which greatly simplifies the fiber drawing process and
25 supports higher doping concentrations but complicates the process of fusion splicing to silica fiber. A quality fusion splice should exhibit low optical loss ($< 0.3 \text{ dB}$), low back reflection loss ($< -50 \text{ dB}$) and good tensile strength ($> 100 \text{ g}$). A standard silica-to-silica fusion splice degrades the
30 multi-component fiber. Instead an asymmetric process that softens only the multi-component fiber is employed as

described in co-pending U.S. application Serial No. 09/963,727 entitled "Method of Fusion Splicing Silica Fiber with Low-Temperature Multi-Component Glass Fiber" filed on September 26, 2001, which is incorporated by reference. To
5 reduce back-reflection, an angle splicing process in which the silica fiber is angle cleaved, the multi-component fiber square cleaved and a matched angle formed in-situ may be employed as described in co-pending U.S. application Serial No. 10/374,001 entitled "Method of Angle Fusion Splicing
10 Silica Fiber with Low-Temperature Non-Silica Fiber" filed on February 25, 2003 the entire contents of which are incorporated by reference.

As shown in figures 6a and 6b, the single mode 2 μ m laser is placed inside a package 50 that provides thermal
15 and vibration isolation. The fiber chain 52 is placed in a mounting fixture 54 having first and second thermally isolated sections 56 and 58 for supporting the narrowband and broadband fiber gratings 14 and 16 respectively. The gain fiber is supported in either the first or second
20 section or in a third isolated section (not shown in this embodiment). Resistive heaters 60 thermistors 61 are mounted on the first and second sections and independently controlled to match the wavelengths of narrowband and broadband gratings.

25 The mounting fixture 54 is connected to the laser external package 50 through connectors 62 made of compliant material with relatively small Young modulus and a small thermal conductivity coefficient. The mounting fixture 54 containing the fiber chain and more specifically the first
30 and second thermally isolated sections 56 and 58 are independently heated above room temperature and temperature

stabilized. The connection to the external package 50 with the compliant connectors 62 provides simultaneously good mechanical and thermal stability to the laser itself. This is necessary for stable laser output.

5 As described above in connection with Figure 1, the optical cavity must be pumped to induce lasing. As shown in Figure 6, a single-mode semiconductor pump diode 22 includes a semiconductor chip 70 and a grating 72 separated by about a meter of passive fiber 74. The grating locks the pump's
10 output to a wavelength. In most applications, the OTS pump diode is adequate. Since, however, very narrow linewidth lasers have a number of applications in sensing, in particular acoustic sensing, it is important to ensure very low frequency and phase noise at low frequencies. The phase
15 noise is particularly sensitive to polarization fluctuations in the pump fiber. Single mode semiconductor pump lasers emit highly polarized light. The polarization of the pump light is, however, sensitive to birefringence fluctuations in the pump fiber if PM fiber is not employed.
20 The fiber 74 that leads from the diode 70 to the fiber laser is typically longer than 1 m and any vibration and acoustic pickup in this fiber leads to small changes in the pump light polarization. Due to the anisotropy of the active ions, this leads to additional noise in the fiber laser
25 output. The effect is more pronounced in the phase noise as in the intensity noise. Ronnekleiv has already pointed out that this vibration and pressure sensitivity could be largely reduced if one would use a depolarized pump source. ["Frequency and Intensity Noise of Single Frequency Fiber
30 Bragg Grating Lasers", by Erlend Ronnekleiv, Optical Fiber Technology, 7, 206-235 (2001) - page 227, second paragraph].

Placing a depolarizer between the highly-polarized pump laser and the fiber laser is one way to reduce the acoustic pickup in the lead fiber.

Using polarization maintaining (PM) fiber 74 from the pump diode 70 to the fiber laser avoids the costly depolarizer and has the same effect. Due to the birefringence in polarization maintaining fiber, the polarization state of the pump light will not change when the fiber is subject to mechanical vibrations or acoustic pressure waves. The polarization whose stimulated emission cross section of the gain fiber is higher is aligned to the orientation of the operating polarization of the narrow-band fiber Bragg grating. Experiments have shown that using PM fiber in the pump lead greatly reduces the phase noise of the fiber laser output and the sensitivity to low frequency external noise.

While several illustrative embodiments of the invention have been shown and described, numerous variations and alternate embodiments will occur to those skilled in the art. Such variations and alternate embodiments are contemplated, and can be made without departing from the spirit and scope of the invention as defined in the appended claims.